On the integration of envelope pressure inhomogeneity and autocorrelation in fan pressurization uncertainty analysis

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ABSTRACT

Improving the knowledge on uncertainty for fan pressurization measurement is of first importance. It allows to assess the reliability of the measurement, which is essential when comparing the results with benchmarks or standards, but it also gives a better understanding, and thus a chance of improving, the measurement procedure. In this context, recent studies on alternative regression techniques highlights the importance of identifying and quantifying the sources of uncertainty. This paper investigates the integration of two new aspects in the measurement procedure: an uncertainty source related to the inhomogeneity of pressure difference along building envelope, and the autocorrelation of successive pressure difference measurement due to wind fluctuations. Those are integrated in the framework of uncertainty calculation and are then applied to a series of 30 tests conducted in repeatability conditions in an apartment in Brussels. Results show the relatively low impact of those additions to the determination of building characteristics (n, C_{env} and q_{50}) and their large impact on both results variability and uncertainty assessment.

KEYWORDS

Fan pressurization test ; Uncertainty calculation ; Autocorrelation ; Measurement functions

1 INTRODUCTION

Fan pressurization test provides the user with a metric related to the capacity of a building to avoid undesired airflows between inside and outside. Furthermore, it is a good indicator of the care taken in the implementation and execution during construction. This test is of first importance, given the importance of air leakage on the energy consumption and occupant's comfort. An indication of the quality of the measurement should always be provided alongside with the test result, since, as expressed in the guide to the expression of uncertainty in measurement: "*without such an indication, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard*" (JCGM, 2008).

Research on the quantification of fan pressurization uncertainties started in mid-90's with (Sherman and Palmiter, 1995). They already mentioned the inadequacy of an OLS (Ordinary Least Square) method to conduct the linear regression required in the post-processing of the data. Recently, (Delmotte, 2017) suggests using WLOC (Weighted Line of Organic Correlation) as an alternative to OLS. Since then, multiple studies (Kölsch and Walker, 2020; Prignon et al., 2020) showed that using WLOC results in a lower uncertainty of the obtained metric, and a better reliability of the calculated uncertainty.

In the WLOC method, each airflow and pressure difference measurements is weighted by its uncertainty. Consequently, while it is not relevant for the OLS method, the WLOC method requires to determine and estimate the different sources of uncertainty. This paper aims at integrating inhomogeneity and autocorrelation in the existing framework for uncertainty analysis. The impact of these new additions is then observed on a series of 30 tests realized in repeatability conditions presented in a previous study (Prignon et al., 2019). Although this paper brings the knowledge about uncertainty in fan pressurization test one step further, it does not pretend to draw up an exhaustive list of uncertainty sources.

The paper is presented as follows. The methodology section illustrates the framework for uncertainty analysis and describes different sources of uncertainty considered in this study, including two new integrated concepts. The methodology section although provides information about the dwelling used for the repeatability study, and the methodology for result analysis. The results of the repeatability study are presented and discussed in the result and discussion sections respectively. Lastly, the paper concludes with a summary of the findings, their limitations and the further work needed in this domain of research.

2 METHODOLOGY

When a measured quantity (y) is a function (f) of multiple input quantities (x_i), one can simply define the measurement function with (1):

$$y = f(x_1, x_2, \dots, x_n) + 0 \qquad (1)$$

Compared to what is generally found in the field of airtightness measurement, this measurement function includes a "plus zero" term that does not alter the value of y. However, in the uncertainty calculation, this term accounts for the fact that the model approximates reality (Mittaz et al., 2019).

The uncertainty of the measured quantity, $u(y)$, is obtained from the measurement function using the propagation law (2):

$$u(y) = \sqrt{\sum_{i=1}^{n} c_i^2 u_c^2(x_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} c_i c_j\, u_c(x_i) u(x_j) r(x_i, x_j)} \qquad (2)$$

In this equation, c_i and c_j are the sensitivity coefficients, $u(x_i)$ is the standard uncertainty related to the input quantity x_i and $r(x_i, x_j)$ is the correlation coefficient linking input quantities x_i and x_j.

2.1 Measurement functions for fan pressurization test

The fan pressurisation test aims to determine the building characteristics (n and C_L) based on multiple measurements of pressure difference – airflow couples (Δp ; q_{env}). This measurement is made of five different steps, and each of them lead to a different measurement function. In this section, uncertainty trees (figures 1 to 3) are used to illustrate the measurement functions and the sensitivity coefficients at each step.

First step is to determine the pressure difference induced by the fan on both sides of the building envelope. In practice, two pressure probes placed inside and outside the building measure a pressure difference (Δp_m), which is the sum of the pressure difference induces by the fan (Δp_f) and by other effects (Δp_0) as such as wind pressure and stack effect. It is not possible to determine which part of the total pressure difference recorded is attributed to Δp_0 and Δp_f while the fan is working. Therefore, Δp_0 is measured before ($\Delta p_{0,1}$) and after ($\Delta p_{0,2}$) the test, and is assumed being constant during the test. Then, the pressure difference induced by the fan measured at the location of the pressure probes (Δp_f) is assumed equal to the pressure difference induced by the fan along the whole building envelope (Δp). Figure 1 illustrates this step with the uncertainty tree related to the pressure difference measurement.

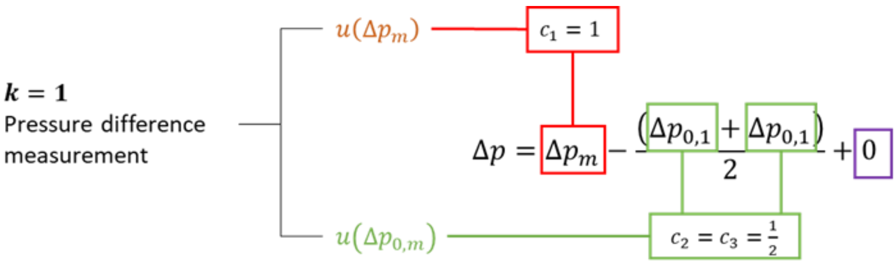

Figure 1: Uncertainty tree for the determination of pressure difference along building envelope.

Second step is the determination of airflow through building envelope openings. Since the mass of air inside the building is assumed constant in steady-state conditions and the pressure difference is considered small compared to atmospheric pressure, temperature ratio is used as a proportionality coefficient between airflow through the fan (q_m) and the building envelope (q_e). Note that, in this study, the uncertainty in temperature measurement is assumed equal for T_i and T_e. Figure 2 shows the uncertainty tree for the second step.

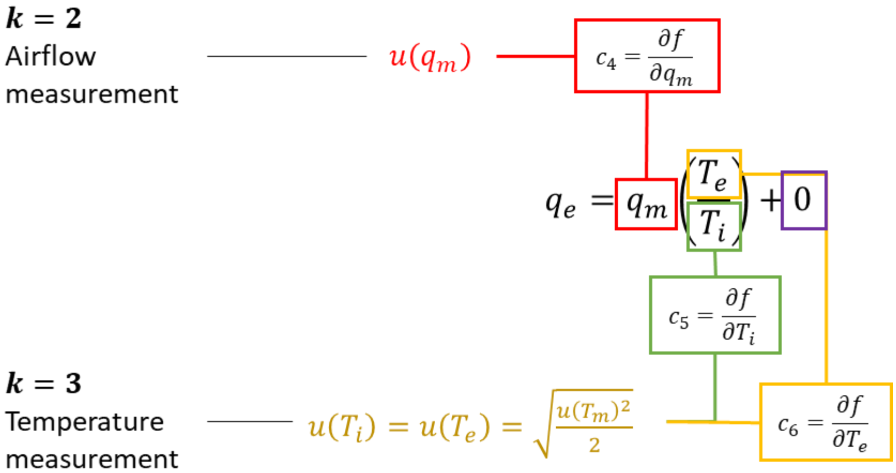

Figure 2: Uncertainty tree for the determination of airflow through building envelope.

Steps one and two provides q_e and Δp, and the combined uncertainty of each. Third step consists in average a series of single point measurements made at the same pressure difference, in order to reduce the uncertainty. Since each measurement is recorded with the same instrument and in a short period of time, those are expected to be correlated. This is particularly true for the pressure difference that is highly impacted by wind direction and speed. In the literature authors generally use a conservative but unrealistic assumption where the uncertainty of the average is equal to the uncertainty of a single measurement (Prignon et al., 2019). This study suggests an alternative between that conservative assumption and the unrealistic hypothesis of uncorrelated measurements: taking into account that variables are autocorrelated. The uncertainty of the average of N fully uncorrelated measurements is given by the variance of the observations divided by N. In case of autocorrelated variable, an effective sample size N_{eff} depending on the level of autocorrelation is considered instead of N in the calculation. This takes into account the fact that a measurement made at time t depends on a series of measurements made before this one (depending on the level of autocorrelation). For a detailed calculation of N_{eff}, the reader should refer to (Warsza, 2013) or (Zhang, 2006).

The fourth step consists in fitting the series of couples (Δp ; q_e) determined at multiple pressure difference with linear regression model. In this study, two different regression techniques are investigated: OLS (generally used) and WLOC (alternative suggested in previous studies). The reader should refer to previous works (Delmotte, 2017; Prignon et al., 2020) for an extended description of those methods and their mathematical expressions. Those regression techniques provide following values as a result: n, $\ln(C_{env})$, $u(n)$, $u(\ln(C_{env}))$ and $r(n, \ln(C_{env}))$.

Building regulations or specifications generally refer to quantities based on the airflow at 50 Pa (q_{50}), which is deduced in the fifth step. While n and $u(n)$ are directly extracted from the regression technique, the determination of the second building characteristics (C_L) referred to in the power law is more complicated. To avoid the complexity of dealing with n and C_L correlation, this study determines q_{50} directly based on n and $\ln(C_{env})$ and does not analyse the behaviour of C_L. Figure 3 shows the measurement function and the uncertainty tree for this last step.

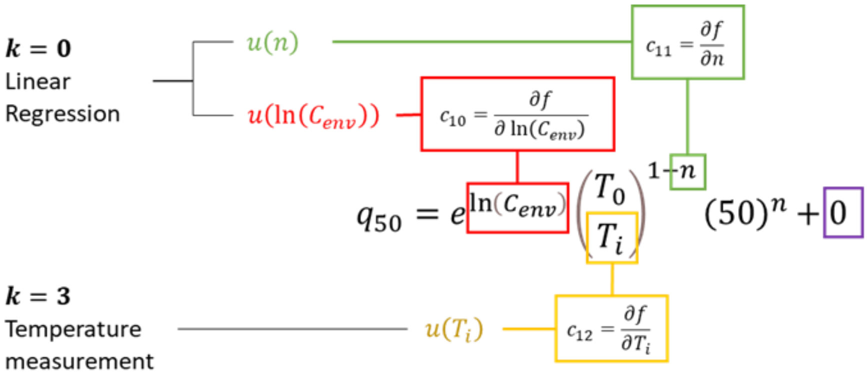

Figure 3: Uncertainty tree analysis for the determination of airflow at 50 Pa.

One may be interested in uncertainty in the combination of pressurization and depressurization, or in derived quantities rather than q_{50}. For both cases the methodology is similar to what was previously showed: define a measurement function that includes the new terms (e.g., building volume for n_{50}). This will also include a new source of uncertainty which must be propagated to the final value. Regarding its lack of interest in a methodological standpoint, those steps are not included in this study.

2.2 Sources of uncertainty

Based on previous section, 9 uncertainty terms divided in three types are included in the process of fan pressurisation measurements (Table 1).

Table 1: Uncertainty terms and type for fan pressurization measurement protocol.

Uncertainty term	Type of uncertainty
$u(T_m)$	Measurement uncertainty
$u(\Delta p_m)$, $u(\Delta p_{0,m})$	Measurement uncertainty
$u(q_m)$	Measurement uncertainty
$u(0_{\Delta p})$	Assumption uncertainty (plus-zero term)
$u(0_{q_e})$	Assumption uncertainty (plus-zero term)
$u(0_{q_{50}})$	Assumption uncertainty (plus-zero term)
$u(n)$	Combined uncertainty from regression
$u(\ln(C_{env}))$	Combined uncertainty from regression

Values for the five terms coming from measurement uncertainty are provided in Table 2. Those are the uncertainty considered in this study, based on the experiment presented in (Prignon et al., 2019), and calculated based on data provided by the manufacturer.

Table 2: Measured quantity and measurement uncertainty for the three measured variables.

Measured quantity	Measurement uncertainty
Airflow rate – $u(q_m)$ [m³/h]	$\sqrt{\left(\frac{\max(0.04*q_m\ ;\ 1.70)}{\sqrt{3}}\right)^2}$
Pressure difference – $u(\Delta p_m)$ and $u(\Delta p_{0,m})$ [Pa]	$\sqrt{\left(\frac{\max(0.01*\Delta p_m\ ;\ 0.15)}{\sqrt{3}}\right)^2+\left(\frac{0.1}{\sqrt{12}}\right)^2}$
Temperature – $u(T_m)$ [°C]	$\sqrt{\left(\frac{0.5}{\sqrt{3}}\right)^2+\left(\frac{0.1}{\sqrt{12}}\right)^2}=0.29$

The uncertainties due to assumptions are included in the uncertainty analysis through the “plus zero” terms in the measurement functions. This study considers two assumptions related to the determination of pressure differences, which should be included in the $u(0_{\Delta p})$ term. Although those hypotheses are often mentioned and discussed in the literature, to the authors’ knowledge only one of them was quantified (H1 hereunder). In this paper, in addition to the previously quantified, one additional hypotheses-related uncertainty component is investigated and quantified (H2).

H1: the zero-flow pressure during the test is defined as the arithmetic mean of the zero-flow pressure measurements conducted before and after the test. This hypothesis was extensively discussed in (Prignon et al., 2021, 2019). Those studies show that the uncertainty strongly depends on the standard deviation of the zero-flow pressure measurements ($\sigma_{\Delta p_0}$) and can be approached with (3):

$$u(\Delta p_{0,a})=\frac{0.11+0.98*\sigma_{\Delta p_0}}{1.35} \tag{3}$$

Although $\sigma(\Delta p_0)$ is easy to obtain during a fan pressurisation measurement, one could consider a conservative value of 1.5 Pa for $u(\Delta p_{0,a})$ in the absence of more information.

H2: the pressure difference between inside and outside the building is homogeneous along the building envelope. This hypothesis is a large approximation and is expected to lead to consequent uncertainties, especially at low pressure measurements. This study suggests a simplified way to quantify this uncertainty term, based on the methodology for uncertainty calculation in the context of climatic chambers. In that field of expertise, the uncertainty due to the inhomogeneity of temperature is defined as the maximum difference observed between two different locations in the chamber, divided by $\sqrt{3}$ (Nakahama, 2007).

To transpose this method for fan pressurization test requires first to determine the distribution of pressure differences along the façade. To that extent, let's consider a simple one-story building with a flat roof. Depending on the façade and the wind direction, the minimum and maximum pressure coefficient are $c_{p,max} = 0.5$ and $c_{p,min} = -0.9$ (ASHRAE, 2009). Those coefficients are then used to compute the minimum and maximum wind pressure, p_w, with (4):

$$p_w = \frac{c_p * v_w^2 * \rho}{2} \tag{4}$$

Where v_w is the wind speed [m/s] and ρ is the air density [kg/m³]. Assuming a constant air density of 1.244 kg/m³, the related uncertainty is deduced from the difference in pressure coefficients along the facade and the wind speed following (5):

$$u(\Delta p_{0,u}) = 0.36 * (c_{p,max} - c_{p,min}) * v_w^2 \tag{5}$$

In this study, the wind speed is known for each test, and $u(\Delta p_{0,u})$ can then be computed individually. Without those information, the user can use the Beaufort scale to define a wind speed based on observations, and compute $u(\Delta p_{0,u})$. H1 and H2 can be combined with (6):

$$u(0_{\Delta p}) = \sqrt{\left(u(\Delta p_{0,a})^2 + u(\Delta p_{0,u})^2 + 2 * r_{\Delta p_{0,a};\Delta p_{0,u}} * u(\Delta p_{0,a}) * u(\Delta p_{0,u})\right)} \tag{6}$$

In this study, the average of 30 repeated test (see section 2.3) showed an average value of $u(\Delta p_{0,u}) = 1.6$ Pa. Since $\Delta p_{0,a}$ and $\Delta p_{0,u}$ are computed for each test, it was possible to deduce $r_{\Delta p_{0,a};\Delta p_{0,u}} = 0.48$. This value seems logical since both terms are largely impacted by wind speed.

Note that this work does not investigate the uncertainty related to the assumptions $u(0_{q_e})$ and $u(0_{q_{50}})$. The uncertainty terms $u(n)$ and $u(\ln(C_{env}))$ are directly deduced from the linear regression process, which is not described here.

2.3 Repeatability testing

To study the impact of those new variables in the fan pressurization measurement protocol, those modified protocols were applied on a series of 30 tests conducted in repeatability conditions. Those tests were performed on a newly constructed apartment within a period of 15 days in October 2017. The apartment was a masonry construction of 228 m³ located on the second floor of a 3-storey building in Brussels. Only two perimetral walls were exposed to the outside. During the tests, a weather station (Ahlborn FMD 760) placed on the roof above the apartment measured the outside air temperature, wind speed and wind direction every 10 s. The wind speed varied from 0.0 to 3.8 m/s during the tests (with an average of 1.3 and a standard deviation of 0.8). A thermometer (Testo 417) was used to measure the inside air temperature before each test. For more details about the tested dwelling, the reader could refer to a previous paper (Prignon et al., 2019).

For each test five different cases are investigated. First is obtained using OLS method, which is not impacted by the source of uncertainty considered in previous section. Other cases are obtained applying WLOC method considering different sources of uncertainties as presented in Table 3.

Table 3: Five cases investigated and their integrated aspects in the uncertainty calculation

Integrated aspects	**WLOC-1**	**WLOC-2**	**WLOC-3**	**WLOC-4**
Measurement uncertainty	X	x	x	x
$u(\Delta p_{0,a})$		x	x	x
$u(\Delta p_{0,u})$			x	x
Autocorrelation				x

3 RESULTS

3.1 Uncertainty in the plus zero term

The two uncertainties related to specific assumptions described previously (H1 and H2) were computed individually for each test. Considering normally distributed data, Table 4 provides average and 95% confidence intervals for those two sources of uncertainty based on the 30 repeated tests.

Table 4: average and 95% confidence interval for $u(\Delta p_{0,a})$ and $u(\Delta p_{0,u})$ for the 30 tests conducted in repeatability conditions.

Uncertainty source	**Average [Pa]**	**95% CI [Pa]**
$u(\Delta p_{0,a})$	1.1	[0.0 ; 2.1]
$u(\Delta p_{0,u})$	1.6	[0.0 ; 4.2]

Based on those values, one can use (6) and previously mentioned information in order to deduce a value of 2.34 Pa for $u(0_{\Delta p})$.

3.2 Effective sample size due to autocorrelation

Autocorrelation is computed individually at each measurement. Figure 4 provides the 95% confidence interval of the effective sample size (N_{eff}) at each pressure difference step for pressurization (red) and depressurization (blue) based on the 30 repeated tests.

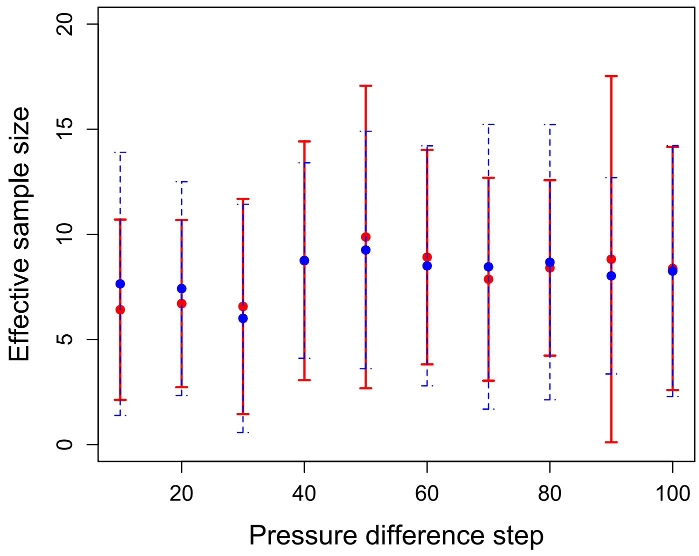

Figure 4: Mean and 95% CI for effective sample size in pressurization (red) and depressurization (blue).

3.3 Impact on building characteristics and uncertainty calculations

Following figures illustrate the values, the observed uncertainty (dash blue) and the calculated uncertainty (red full) of n, $\ln(C_{env})$ and q_{50} in pressurization and depressurization for each investigated case. Note that the exact values are given in tables in appendix.

For n and $\ln(C_{env})$, same observations are found and illustrated in Figure 5 and Figure 6 respectively. The observed uncertainty is lower for WLOC-2 and WLOC-3 than for other cases. WLOC-2 and WLOC-4 are the cases where the calculated uncertainty is the more reliable (i.e., smaller difference between observed and calculated uncertainty). Note that the uncertainty calculated with WLOC-3 largely overestimates the observed uncertainty. This was expected since two new terms increase the uncertainty, without considering the reduction due to the autocorrelation aspect.

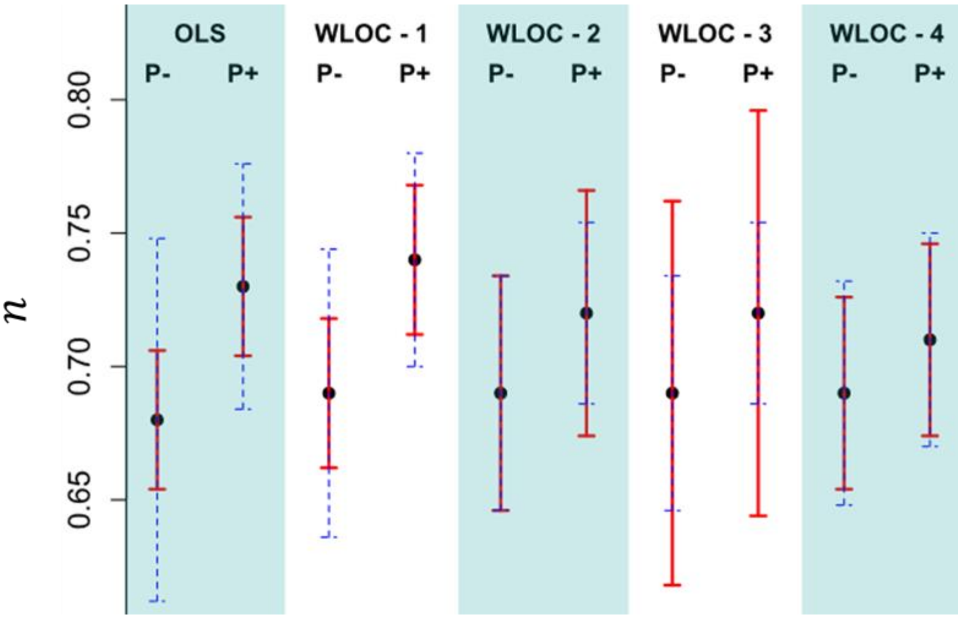

Figure 5: average (black dot), observed uncertainty (blue dashed line) and calculated uncertainty (red full line) for n for the 5 investigated cases based on 30 repeated fan pressurization tests.

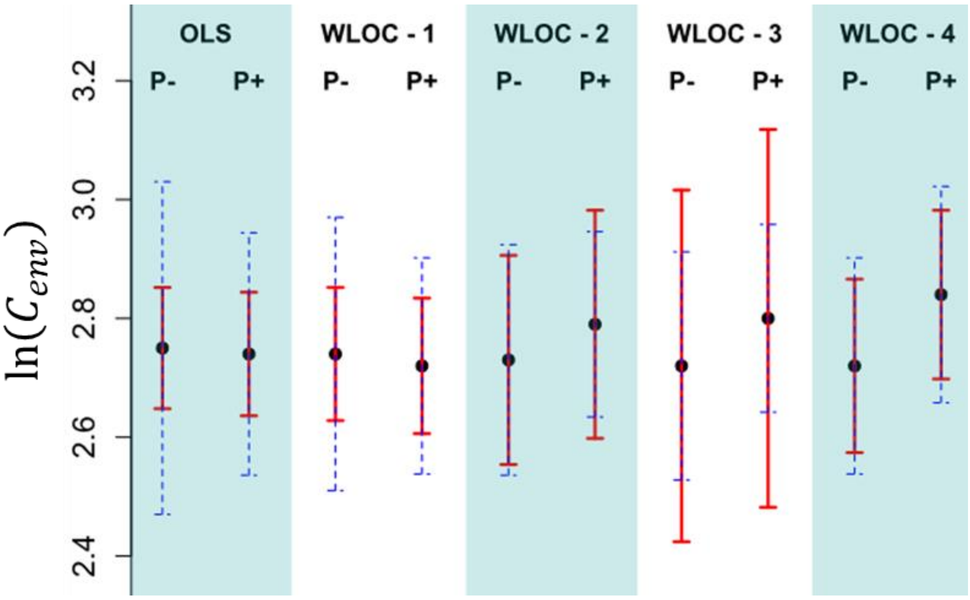

Figure 6: average (black dot), observed uncertainty (blue dashed line) and calculated uncertainty (red full line) for $\ln(C_{env})$ for the 5 investigated cases based on 30 repeated fan pressurization tests.

Figure 7 shows that the observations made for n and $\ln(C_{env})$ are not translated to q_{50}. In that case, the most reliable uncertainty calculation is for WLOC-3 while other are found performing equivalently.

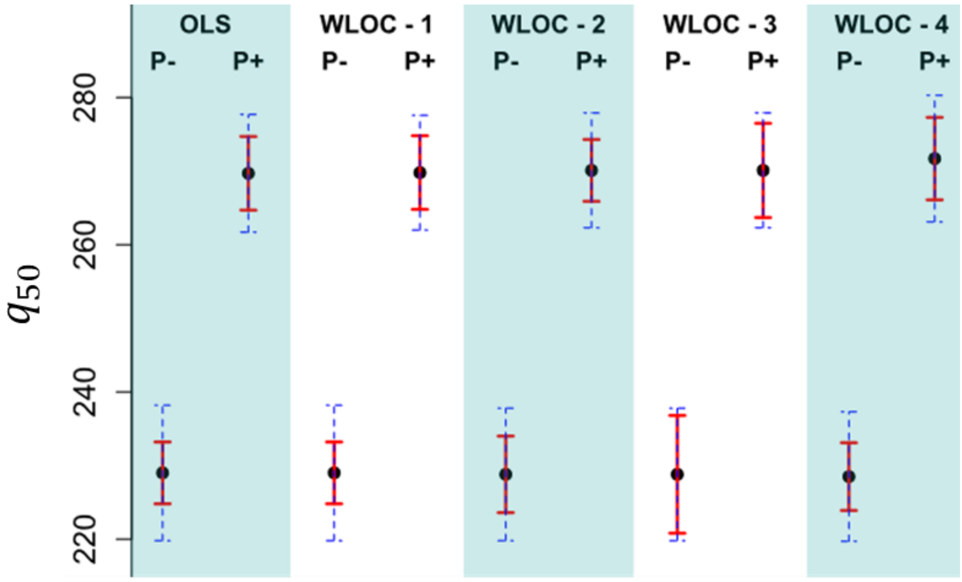

Figure 7: average (black dot), observed uncertainty (blue dashed line) and calculated uncertainty (red full line) for q_{50} for the 5 investigated cases based on 30 repeated fan pressurization tests.

4 DISCUSSION

The results presented in section 3.2 have three main outcomes. First, the uncertainty observed on n and $\ln(C_{env})$ are lower when using WLOC methods than when using OLS method. This is in line with existing literature and is confirmed in this study since it is found for all cases of WLOC, whatever the uncertainty sources considered (WLOC 1 to 4). Second, the fit between observed and calculated uncertainties for flow exponent and flow coefficient are found good for WLOC – 2 and WLOC – 4, and poor for WLOC – 3. Consequently, the inclusion of the new suggested uncertainty term $u(\Delta p_{0,u})$ should always be considered when taking into account the autocorrelation of pressure difference measurement (WLOC – 4) since the conservative assumption $N_{eff} = 1$ used in previous studies induces and overestimation of the uncertainty. Third, the trends observed for n and $\ln(C_{env})$ hereabove are not transferable to airflow at 50 Pa. It was showed in previous research that the improvement using WLOC found for airflow exponent and air leakage coefficient is not seen at 50 Pa (Prignon et al., 2020), but is well found at higher and lower pressure differences. This can be explained either by a problem in the calculation of the correlation between n and $ln(C_{env})$, or by the fact that this is not an exhaustive list of uncertainties. Other sources of uncertainty could be considered in the framework including, but not limited to, the location of the pressure probe, the impact of wind on airflow measurement and the deterioration of the equipment over time. The calculation for inhomogeneity of pressure difference along the envelope (section 2.2) could be adapted to consider the location of the pressure probe. However, this would require to study the pressure fields around the building.

Those observed trends are case specific. While the methodology – including the formulae - should be transferable to other cases, specific attention should be paid to using the suggested values of this paper when applying this to building of different shapes and sizes. This is especially true for buildings where the stack effect plays a large role in the Δp_0 measured.

5 CONCLUSION

This study investigates how the integration of two new aspects in the framework of uncertainty analysis impacts the fan pressurization test regarding the calculated and the observed uncertainties of n, $\ln(C_{env})$ and q_{50}. The study demonstrates that the use of WLOC should be preferred over OLS, but the choice of sources of uncertainty should be carefully conducted. It also provides methods to integrate the inhomogeneity of envelope pressure difference and the autocorrelation of pressure difference measurements in the uncertainty analysis. These results brings the scientific community one step further in the uncertainty analysis for fan pressurization measurements.

Although the study provides strong and useful results, two limitations inherent to the methodology should be mentioned. First, the conclusion are driven by a set of tests conducted on one specific building. Although those trends are expected to be found for other buildings, this generalization work is still to be done, especially when considering the values found in this study for $u(\Delta p_{0,u})$ and N_{eff}. Second, by definition the repeatability testing consider only precision errors since bias errors are expected to repeat from one test to another. Consequently, this study does not consider the bias errors that could be included in the fan pressurization test. In addition, the repeatability testing does not include the uncertainty related to a change in the operator since all tests are performed by the same person. This is expected to have a strong impact on the uncertainty of fan pressurization measurements as showed by (Delmotte and Laverge, 2011).

This work highlights the fact that uncertainties are still not well quantified for fan pressurization test. Further work should focus on having a better understanding of the sources of uncertainty through the generalization of the trends observed in this study, and on the study of a more comprehensive list of sources of uncertainty. This in order to improve the measurement method and to provide a reliable uncertainty value when conducting the experiment.

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7 APPENDIX

Table 5: average, observed and calculated uncertainties for the flow exponent in pressurization.

Quantities	OLS	WLOC-1	WLOC-2	WLOC-3	WLOC-4
Average calculated value (n)	0.73	0.74	0.72	0.72	0.71
Standard deviation ($u_0(n)$)	3.2 %	2.8 %	2.4 %	2.4 %	2.9 %
Average calculated uncertainty ($u_c(n)$)	1.8 %	2.0 %	3.2 %	5.3 %	2.5 %

Table 6: average, observed and calculated uncertainties for the flow exponent in depressurization.

Quantities	OLS	WLOC-1	WLOC-2	WLOC-3	WLOC-4
Average calculated value (n)	0.68	0.69	0.69	0.69	0.69
Standard deviation ($u_0(n)$)	4.9 %	4.0 %	3.3 %	3.2 %	3.1 %
Average calculated uncertainty ($u_c(n)$)	1.9 %	2.1 %	3.1 %	5.2 %	2.6 %

Table 7: average, observed and calculated uncertainties for the flow exponent in pressurization.

Quantities	OLS	WLOC-1	WLOC-2	WLOC-3	WLOC-4
Average calculated value ($\ln(C_{env})$)	2.74	2.72	2.79	2.80	2.84
Standard deviation ($u_0(\ln(C_{env}))$)	3.7 %	3.3 %	2.8 %	2.8 %	3.2 %
Average calculated uncertainty ($u_c(\ln(C_{env}))$)	1.9 %	2.1 %	3.4 %	5.7 %	2.5 %

Table 8: average, observed and calculated uncertainties for the flow exponent in depressurization.

Quantities	**OLS**	**WLOC-1**	**WLOC-2**	**WLOC-3**	**WLOC-4**
Average calculated value ($\ln(C_{env})$)	2.75	2.74	2.73	2.72	2.72
Standard deviation ($u_0(\ln(C_{env}))$)	5.1 %	4.2 %	3.6 %	3.5 %	3.4 %
Average calculated uncertainty ($u_c(\ln(C_{env}))$)	1.9 %	2.0 %	3.2 %	5.5 %	2.7 %

Table 9: average, observed and calculated uncertainties for the flow exponent in pressurization.

Quantities	**OLS**	**WLOC-1**	**WLOC-2**	**WLOC-3**	**WLOC-4**
Average calculated value (q_{50})	270	270	270	270	272
Standard deviation ($u_0(q_{50})$)	2.0 %	2.0 %	2.0 %	2.0 %	1.9 %
Average calculated uncertainty ($u_c(q_{50})$)	0.9 %	0.9 %	1.1 %	1.8 %	1.0 %

Table 10: average, observed and calculated uncertainties for the flow exponent in depressurization.

Quantities	**OLS**	**WLOC-1**	**WLOC-2**	**WLOC-3**	**WLOC-4**
Average calculated value (q_{50})	229	229	229	229	229
Standard deviation ($u_0(q_{50})$)	1.5 %	1.5 %	1.4 %	1.4 %	1.5 %
Average calculated uncertainty ($u_c(q_{50})$)	0.7 %	0.7 %	0.9 %	1.3 %	0.7 %